currents differing 90° in phase. The object of this arrangement was stated to be to obtain a larger output—which is, indeed, true, since the output of a polyphase machine is considerably higher than that of any other of equal weight. It was also stated that the machine could be used as a motor, though nothing was said about the properties of the rotatory field. Claim 9 runs as follows: "A rotary electric motor consisting of a field-magnet and armature and pairs of current-leading devices—such for instance as contact-rings and brushes—the respective pairs being independently connected into the armature winding at alternating points of the same, and arranged for connection with two independent external circuits."

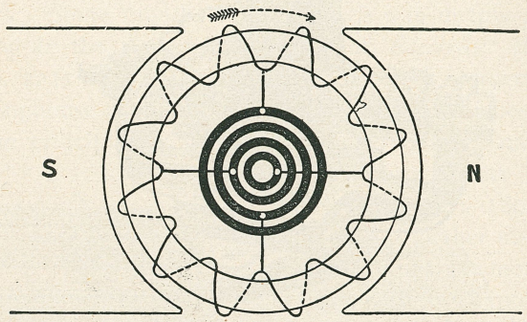

FIG. 337.

Here was, then, in 1887, a polyphase motor unmistakably described. In October 1888 (patent No. 404465) comes an asynchronous motor, driven by means of directed eddy-currents in a stationary external mass of iron. The rotating inductor received two-phase currents through four slip-rings. The whole principle of magnetic slip is fully explained.

In a patent (No. 409450), published August 20th, 1889, Bradley describes a similar armature tapped at three equidistant points and connected to three slip-rings, thus constituting a three-phase system. This machine also was for use as either generator or as motor. In another patent of same date, Bradley indicates a method of splitting a single-phase alternate current into two of different phases by use of his machines.

Researches of Nikola Tesla.—The work done by Nikola Tesla between the years 1887 and 1891 is of itself sufficient, had no other workers been occupied in the same field of research, to have established the rotatory-field motor upon a solid basis. He arrived in 1886 at the firm conviction that some method must exist of driving an armature by currents induced within it, instead of driving it by currents brought into it (as in the ordinary electric motors) through the agency of metallic contacts, commutators and brushes. By October 1887 Tesla's work was sufficiently advanced for him to apply to the United States Patent Office for patents covering numerous points of a more or less fundamental character. Other applications for patents followed in November and December of the same year, but none were issued from the Patent Office until May 1888, when a whole batch of them were granted.

The first of these specifications set forth the general scope of Mr. Tesla's ideas. He says, "Though I have described various means for the purpose, they involve the same main principles of construction and mode of operation, which may be described as follows: A motor is employed in which there are two or more independent circuits through which alternate currents are passed at proper intervals, in the manner hereinafter described, for the purpose of effecting a progressive shifting of the magnetism or the lines of force in accordance with the well-known theory, and a consequent action of the motor. It is obvious that a progressive shifting of the lines of force may be utilised to set up a movement or rotation of either element of the motor, the armature or the field-magnet, and that if the currents directed through the several circuits of the motor are in the proper direction no commutator will be required; but to avoid all the usual commutating appliances in the system, I prefer to connect the motor circuits directly with those of a suitable alternate-current generator." He then proceeds to describe by a diagram (Fig. 338, which is taken from Fig. 9 of the specification) how a generator is wound with two separate coils, the free ends of which are connected to insulated contact-rings on the shaft. From four

brushes that press on the rings, four wires are led away to the motor. This is, in fact, a simple two-phase generator, inducing two currents in quadrature. The motor is shown as a ring built up of core-sheets, having wound upon it four coils, two of which are connected in circuit with one pair of wires, the other two being in the other circuit. They tend to co-operate in pairs, to produce magnetic poles on diametrically opposite parts of the ring. Within the ring is pivoted as rotor a disk D of iron, preferably cut away at its sides so as to form an elongated body, and turns so as to convey from side to side of the ring the greatest number of magnetic lines.

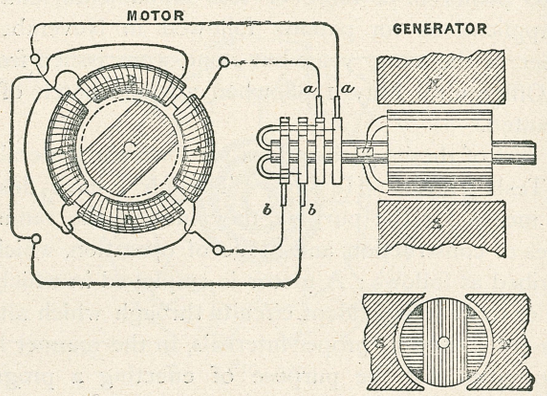

FIG. 338.

It was found that this form was not essential to rotation, since a circular disk of iron was also set revolving. This phenomenon Mr. Tesla attributed to a certain magnetic inertia or resistance to shifting of the magnetic lines; and deemed this view confirmed by the observation that a circular disk of steel is more effectively rotated than one of soft iron. In a series of eight diagrammatic figures Mr. Tesla explained the successive phases through which the coils of the generator pass during one revolution, and the corresponding and resulting changes of magnetism produced in the ring of the motor. The resultant direction of the magnetic field shifts progressively round (Fig. 339), dragging the iron disk with it.

This combination amounts, then, to a two-phase synchronous motor not operating by induced currents in the rotor, but by magnetic reactions, together with a suitable two-phase generator for supplying the current.

Other forms were described at the same time. A motor had a drum armature wound with two coils at right angles, to which the currents were brought by four slip-rings. This armature revolved between the two parts of an exterior shell of iron or steel, which to *prevent* eddy-currents (!) was preferably to be laminated. It was not wound, being magnetised solely by the polarity of the armature. Then followed a three-phase generator and motor on similar lines to the two-phase generator and motor first described. The generator had three revolving coils and six slip-rings. It was connected by six line-wires to the ring of the motor, which had six coils wound upon six inward-pointing poles, constituting a 2-pole field with three phases. The rotor was as before a disk or cylinder of iron cut away on two sides to form an elongated body. The next form described was a two phase combination, having in the generator a revolving magnet and two pairs of fixed armature coils, while the motor had as before a cut-away disk of iron as rotor, surrounded by two fixed coils set at right angles to one another. A form of motor was shown having arrangements for bringing the two phase currents to its revolving windings as well as to windings on a fixed external ring. It was found to be advantageous in the case where an external iron shell or fixed magnet was employed to give this a fixed magnetic polarity by separately exciting it with a continuous current. These motors were, of course, synchronous. Transformers

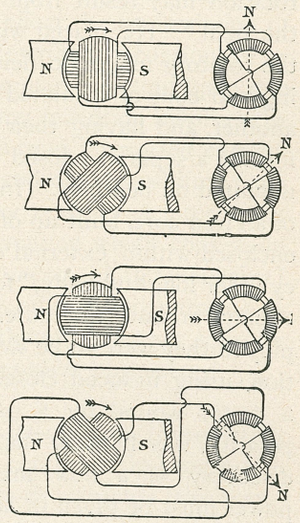

FIG. 339

for currents such as were used in these systems were made by winding a set of primary and a set of secondary wires upon the same ring of laminated iron, in which the magnetism underwent a progressive shifting of polarity. In November came the first suggestion of a real induction motor. Hitherto Mr. Tesla had produced and maintained the rotation by the "direct attraction" of the magnetic elements of the motor. "I have discovered," he says, "that advantageous results may be secured in this system by utilising the shifting of the poles primarily to set up currents in a closed conductor located within the influence of the field of the motor so that the rotation may result from the reaction of such currents upon the field." He placed within the ring that was to generate the rotatory magnetic field a soft iron cylinder or disk, carrying two coils of insulated wire wound at right angles to one another, and having their respective ends joined so that each formed a separate closed circuit; this was placed on an axis mounted on bearings. In another form the rotor was formed of an iron core, built up of disks to prevent eddy-currents, and enclosed within external coils or conductors, "applied to the cylinder longitudinally," formed into one or more independent circuits around the core. If copper plates were thus employed they were to be slotted longitudinally. This construction, using induced closed circuits on the revolving part of a motor wound for a progressive shifting of the magnetic polarity, was broadly claimed. The still wider claim of the discovery of a new method of electrical transmission of power must be given in Mr. Tesla's own words:—

"I am aware that it is not new to produce the rotations of a motor by intermittently shifting the poles of one of its elements. This has been done by passing through independent energising coils on one of the elements, the current from a battery or other source of direct or continuous currents, reversing such current by suitable mechanical appliances, so that it is directed through the coils in alternately opposite directions. In such cases, however, the potential of the energising currents remains the same, their direction only being changed. According to my invention, however, I employ true alternating currents; and my invention consists in the discovery of the mode or method of utilising such currents.

"The difference between the two plans and the advantages of mine are obvious. By producing an alternating current, each impulse of which involves a rise and fall of potential, I reproduce in the motor the exact conditions of the generator, and by such currents and the consequent production of resultant poles, the progression of the poles will be continuous and not intermittent. In addition to this, the practical difficulty of interrupting or reversing a current of any considerable strength is such that none of the devices at present could be made to economically or practically effect the transmission of power by reversing in the manner described a continuous or direct current. In so far, then, as the plan of acting upon one element of the motor is concerned, my invention involves the use of an alternating as distinguished from a reversed current, or a current which, while continuous and direct, is shifted from coil to coil by any form of commutator, reverser or interrupter. With regard to that part of the invention which consists in acting upon both elements of the motor simultaneously, I regard the use of either alternating or reversed currents as within the scope of the invention, although I do not consider the use of reversed currents of any practical importance.

"What I claim is—

"The method herein described of electrically transmitting power, which consists in producing a continuously-progressive shifting of the polarities of either or both elements (the armature or field-magnet or magnets) of a motor by developing alternating currents in independent circuits, including the magnetising-coils of either or both elements, as herein set forth."

The documents filed by Mr. Tesla, in the United States Patent Office in the autumn of 1887, are very comprehensive; they deal with synchronous forms of motors as well as non-synchronous, with polyphase generators with methods of transmission, with polyphase transformers, and illustrate many forms of machines combined in various ways. These include

not only the two-phase system of transmission with four wires described above, but also a three-phase system of transmission using six-line wires. The principle of the progressive shifting or rotation of the magnetism in the motor runs through the whole of these patents from the first. The principle of slip was enunciated in No. 382279, filed on November 30, 1887, in which specification it is also pointed out that the direction of the rotation may be reversed by reversing the connexions of one of the circuits coming from the generator.

In April 1888, Tesla finds he can use a common return in a two-phase system, and so reduces the four wires to three. He also shows how to take off two-phase currents from an ordinary continuous-current dynamo, by providing it with four slip-rings which are severally joined to four symmetrical points on its commutator. Passing on to generators which (like the well-known Thomson-Houston arc-light dynamos) have three coils united at a common joint, with their free ends connected to the segments of a commutator, Tesla shows that by connecting each of the three ends to a separate slip-ring with collecting brushes, three alternating currents can be taken off. These will be in three symmetrical phases. He suggests that in this case the motor or transformer should also be furnished with three energising coils placed symmetrically.

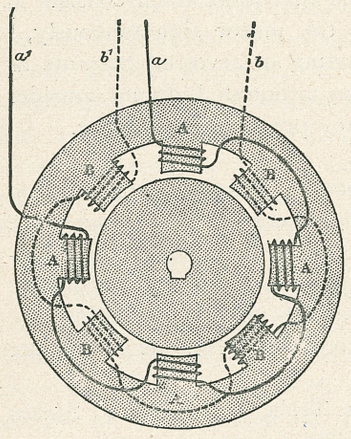

FIG. 340.—MULTIPOLAR DESIGN.

From an early period in his researches Tesla seems to have grasped the importance of multipolar designs in reducing the speed. In May 1888, he already had multipolar synchronous motors, and later this feature developed. Fig. 340 shows a design of a 4-pole field having four poles in the A circuit (alternately N and S poles), and four intermediate poles in the B circuit.

In such a case the progression of the field is not a uniform rotation. The field of a pole at A does not shift round to the next pole at B. What happens is that the magnetism of the A pole dies out, while fresh magnetism grows in the neighbouring B pole. The polarity, in fact, shifts by jumps from one pole-piece to the next.

In April 1889, Tesla describes methods of operating two-phase motors from an ordinary (single-phase) alternate current, by using the device of *splitting the phase*, for starting synchronous motors; putting the two sets of coils in parallel with a non-inductive resistance in one branch (see Fig. 341)

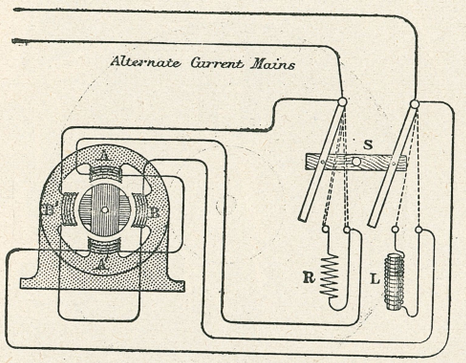

FIG. 341.—PHASE-SPLITTING DEVICE.

and a self-inductive resistance (or choking-coil) in the other branch. When the motor has started these are cut out; but the motor continues to revolve as a synchronous motor. This device was not claimed generally by Tesla, and wisely, since it had already been used by Ferraris (page 442); but he claimed it as a means of starting a synchronous motor. His words are:—"I believe I am the first to operate electromagnectic motors by alternating currents . . . . by producing a progressive movement or rotation of their poles or points of greatest magnetic attraction by the alternating currents until they have reached a given speed, and then by the same currents producing a simple alternation of their poles, or, in other words, by a change in the order or character of the

circuit connexions to convert a motor operating on one principle to one operating on another for the purpose described." None but synchronous motors appear to be contemplated.

This was followed by other patents for various species of split-phase motors, including one illustrated in Fig. 342, in which there are two sets of coils to be united in parallel to ordinary alternate-current mains. The coils of one set were wound of thick wire on long iron cores, having much self-induction and small resistance; the others were wound on very short poles with wire of high resistance. The result is to retard the currents through the former as compared with the latter, and so establish a progressive shifting of polarity.

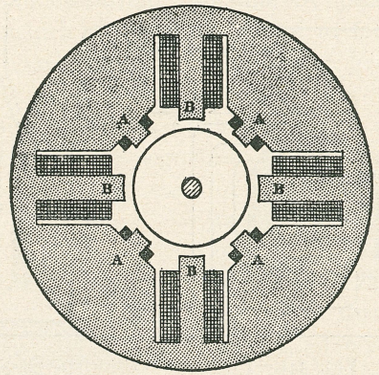

FIG. 342.—SPLIT-PHASE MOTOR.

Sundry other forms were devised between 1889 and 1891, when the series closed with a form of 6-pole motor, in which the desired difference of phase was produced in one set of coils by the use of a condenser excited by currents in a secondary winding. This important series of patents passed into the possession of the Westinghouse Company. For fuller accounts of Tesla's work see his lecture of May 1888, before the American Institute of Electrical Engineers; also the volume on Tesla's Inventions by Mr. T. C. Martin.

Haselwander's Motors.—In the summer of 1887, Haselwander, an engineer of Offenburg (Baden), constructed a three-phase machine of about 10 horse-power, having a stationary

ring-armature 40 centimetres in diameter, wound with 12 coils, and an internal revolving 4-pole field-magnet. It had also a commutator to excite its own field-magnet. It was exhibited in 1891 at the Frankfort Exhibition. Haselwander's leading idea was as follows:—Every ordinary dynamo or motor for

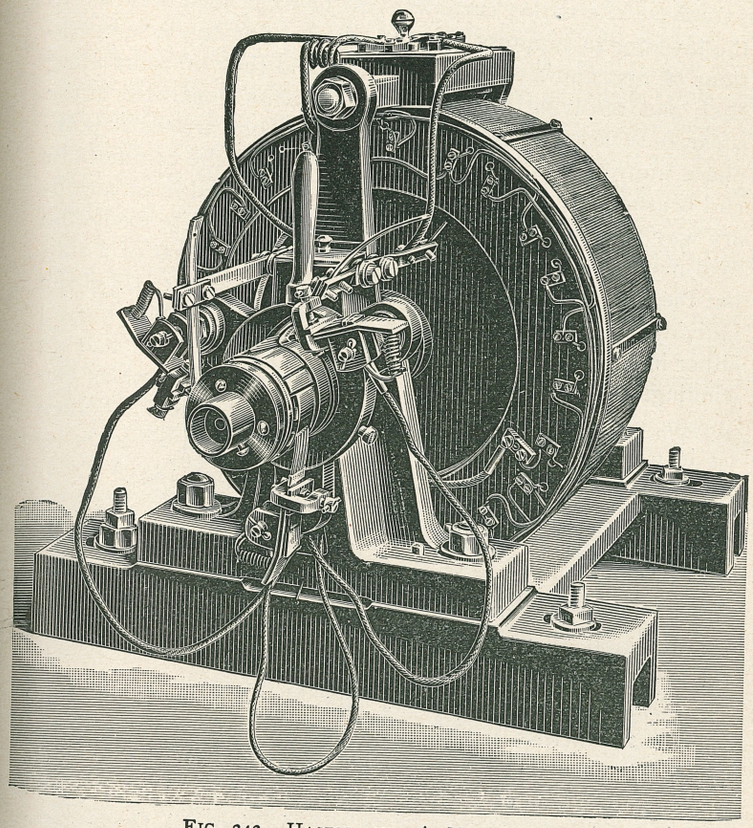

FIG. 343.—HASELWANDER'S MOTOR (1887).

continuous currents really generates in its successive groups of coils alternating electromotive-forces in different phases; and the commutator serves to change these polyphase currents into an overlapping succession of uni-directional currents. In the transmission of power by means of continuous currents,

two such continuous-current machines are joined together by two conducting lines. The pulsating continuous current given off by the primary machine (or generator) is again resolved into its components by the commutator of the secondary machine (or motor), and returns to the form of a series of polyphase alternating currents. So now the idea occurred to the inventor to suppress the two similar but converse operations of first uniting and commuting, and then of commuting back and resolving the polyphase currents generated in the separate sections of the armature. Thus one arrives at polyphase transmission of power and suppresses the commutator and brushes, except so far as these may be used in an auxiliary way to divert a small fraction of the currents to excite the field-magnets. The grouping of the coils was that of a star, but the coils were provided with terminals which enabled the individual coils in each of the three phases to be grouped either in series or in parallel. Each of the 12 coils had 52 windings of 1·52 millimetre wire. At 960 revolutions per minute, a current of 24 amperes at 100 volts could be taken off in each phase. This machine is described in a lecture by Dr. J. Epstein, in the *Electrotechnische Anzeiger*, 1891.[1]

Wilson's Motor.—In a patent specification (No. 18525 of 1888) E. Wilson describes a two-phase motor having an armature of ring or drum type, with commutator. Two-phase currents were supplied to both field-magnets and armature, the direction of rotation being controlled by the position of the brushes.

Wenström's Motors.—The late Mr. Wenström in 1890 took out a British patent (No. 5423 of 1890) for a three-phase system. He describes, and gives a remarkably clear winding diagram of a three-phase generator. He proposed to join up the three windings in star fashion. A three-phase transformer and a three-phase motor are also included in the specification.

M. von Dolivo-Dobrowolsky's Researches.—M. von Dolivo-Dobrowolsky is now the chief electrician of the Allgemeine

[1] See also the official report of the Electrotechnical Exhibition at Frankfort of 1891 (pub. 1893), 251; also *Elektrotechnische Zeitschrift*, 1891, pp. 540 and 609.

Elektricitäts-Gesellschaft of Berlin. To him we owe the term "Drehstrom" (originally applied to the connected three-phase system), to denote a polyphase system of currents.

The first of Dobrowolsky's British patent specifications (No. 10933 of 1889) relates to the rotors of polyphase machines, and refers specifically to the production by Ferraris of rotatory fields in which conducting bodies are acted upon by eddy-currents induced in them. The proposal was to use as rotor an iron body in which there are set conductors or veins of copper, bars or strips, arranged so as to be transverse both to the direction of rotation and to the lines of the field; these conductors or strips being short-circuited at their ends. The drawings show simple forms of short-circuited rotors (including a "squirrel-cage") with solid iron bodies.

The next two patents (19554 and 19555 of 1889) relate to a form of polyphase generator and to a three-phase transformer. The latter had a three-branched core, the magnetic circuit forming a star combination.

In August 1890, comes specification No. 13260 of that year, with the device of adding to the common junction of a three-phase (or *n*-phase) system a common return, so as to render the three (or more) circuits independent of one another, and with regulating apparatus to control the pressure in each of the circuits. Two three-phase adjustable auto-transformers are described, one of them being for long-distance work; and a combination of three separate transformers is also described.

Specification No 20425 of 1890 describes a laminated rotor wound with insulated coils; and after pointing out how, at starting, the reaction of the rotor currents interferes with the field produced by the primary currents and diminishes the torque, proposes the method of introducing into the rotor circuit resistances capable of regulation. Liquid resistances are shown in the drawings.

In specification No. 3191 of 1891, Dobrowolsky shows polyphase transformers for changing currents of any number of different phases into a three-phase system, together with methods of transforming three-phase currents into a larger

number of phases. And in No. 13503 of the same year he describes his method of obtaining currents of intermediate phase by combining mesh and star systems. For instance, he showed how in a three-phase system six phases of currents could be produced from the three line wires by six coils, three of which were in series severally with the three lines, and the other three joined as shunts across the lines; all six coils being spaced out properly on the inductor-core (see Fig. 61, page 57). By the introduction of these intermediate phases, Dobrowolsky proposed to make the torque (which in the absence of reactions from the rotor would fluctuate between certain maximum and minimum values in each complete period) more constant. In a large number of figures these various modes of concatenation of circuits and phases were elaborated.

THE FRANKFORT EXHIBITION, 1891.

Nothing more clearly marks the entrance of polyphase machinery into the electrical industry than the Electro-technical Exhibition held at Frankfort-on-the-Main in the summer of 1891. This exhibition was rendered famous by the now historical transmission of 100 horse-power over 100 miles of line. It also revealed a striking development of polyphase machinery in general. Though nominally an International Exhibition the exhibits were mainly by German firms; and the feature of greatest interest were the polyphase apparatus contributed by many firms. The official report[1] gives many illustrations of these, together with the tests carried out during several months by the jury of experts. The following notes as to the exhibits of this class are extracted from this report.

Messrs. W. Lahmeyer and Co., of Frankfort, sent out from their model central station in the Machine-hall a three phase current at 75 volts, which worked several three-phase motors, including the historic machine of Haselwander (Fig.

[1] *Allgemeiner Bericht über die Internationale Elektrotechnische Ausstellung in Frankfurt am Main*, 1891, 2 vols., published Frankfort, 1893.

343, page 455), a 10 horse-power synchronous motor of the ordinary 4-pole Lahmeyer type, but provided with three slip-rings instead of the usual commutator, and a number of small motors.

Messrs. Schuckert and Co. had two large two-phase generators with armatures of their well-known flat-ring type, provided with slip-ring. One of these machines was in the Machine-hall and furnished power to the pumping station on the Main; the other, situated more than a mile away, at the Palm-garden, supplied power to the Distribution-hall in the Exhibition. As the ring-winding of these armatures was joined up in a mesh (Fig. 49, page 53), it was necessary to employ two independent circuits with four lines in total; but by the introduction of transformers (compare Fig. 273), it was possible to use a three-wire system of transmission to a distance. Similar machines, with constantly-excited field-magnets, were used as motors. They ran synchronously, and with a greater output than if used as asynchronous motors without separate excitation. The 25 horse-power machine used as motor in the exhibition had, indeed, an auxiliary commutator to enable it to excite its own magnets. The 50 horse-power motor at the pumping station was separately excited. The transformers employed were also of flat-ring form, the coils being wound in grooves planed out from a core built up of hoop-iron wound up in a close spiral.

Messrs. Siemens and Halske showed some small three-phase motors, one type having a closed-circuit rotor; another having a rotor provided with a commutator into which the three-phase currents were led by three equidistant brushes after having traversed the three circuits of the windings on the stator. They also exhibited two three-phase generators: one resembling their ordinary alternator, having as armature a set of 24 bobbins (in three series of eight bobbins each) revolving between two crowns of 16 alternate poles; the other on the lines of their ordinary continuous-current dynamos, having a drum armature connected at three equidistant points of the winding to three slip-rings.

The Allgemeine Elektricitäts-Gesellschaft, of Berlin, had,

in conjunction with the Oerlikon Machine Company, of Zurich, undertaken the striking demonstration of long distance transmission of power at high voltage from Lauffen to Frankfort, which is further described below. This was a three-phase (or so-called *Drehstrom*) transmission. The 100 horse-power motor in the Exhibition, which received current from Lauffen 110 miles away, was employed to pump water to supply an artificial waterfall. It is depicted in Fig. 351, page 469. A smaller three-phase motor[1] of about 3 horse-power, used to drive a small continuous-current dynamo with a load of lamps, had a construction the inverse of that now usual in induction motors. The currents were led by three slip-rings into a revolving armature, whilst a stationary external part, consisting of iron core-rings furnished with closed circuit winding, constituted an induced field-magnet. A still smaller motor with induction rotor without contacts served to drive a small fan. Other motors exhibited at the same place by the Oerlikon Company, constructed from Brown's designs, had the now usual construction of a fixed external armature built of core-rings pierced to receive the windings; while the rotor was also built of pierced core-rings with a simple copper circuit of bars short-circuited with two end-rings like a squirrel-cage. One of these, of 20 horse-power, at 1200 revolutions per minute, weighed only 420 kilogrammes.

THE LAUFFEN-FRANKFORT TRANSMISSION.

At Lauffen, near Heilbronn, the River Neckar has a fall of about 12 feet. The power had for some years been partially utilised for a cement factory; of the 1500 available horse-power about 1200 was taken up by turbines, but enough remained to furnish 200 or 300 horse-power, and it was proposed to utilise this for lighting the town of Heilbronn 6 miles distant. While this project was under consideration, came the suggestion, in the autumn of 1890, to seize the opportunity afforded by the Frankfort Exhibition to show what could be done in the way of transmitting power to a long distance at

[1] Now in the laboratory of the Technical College, Finsbury.

high voltage, and at the same time to demonstrate the advantages of the *Drehstrom* or polyphase system. Lauffen is 110 miles from Frankfort. To transmit, as was proposed, 100 horse-power through three copper wires, each only 4 millimetres thick, and with an efficiency of at least 75 per cent., necessitated the employment of a pressure of no less than 8000 volts. This *tour de force* was nevertheless accomplished. The engineer of the line and of the Lauffen generating station was Mr. Oscar von Miller, of Munich. With him were associated in harmonious action two great commercial firms, the Allgemeine Elektricitäts-Gesellschaft, of Berlin, and the Oerlikon Maschinen-Fabrik, of Zürich. They had the cordial co-operation of the Imperial German Post Office in the difficult task of laying out and constructing the line.[1] The copper wire was lent for the purpose by the firm of Hesse, in Hedderheim. The two three-phase generators constructed by the Oerlikon Company were driven by turbines; and after the end of the exhibition were applied to this service, and are still in use. They were previously designed for supplying current to the town of Heilbronn, 6 miles distant. They were constructed from the designs of Mr. C. E. L. Brown, and have revolving internal field-magnets with an external armature with zigzag arrangements of conductors passing through holes in the core-rings. Fig. 344 gives a general view, whilst Fig. 345 shows the field-magnet after the armature has been slid away for inspection. The machine generates three currents, each of 1400 amperes, at a pressure of about 50 volts; taking 300 horse-power when running at 150 revolutions per minute. The armature has an external diameter of 189·4 cm. (nearly 6 feet) and an internal diameter of 176·4. The total thickness of core-rings, parallel to the shaft, is 38·0 cm. Around the inner periphery of the core-rings are 96 circular holes 33 mm. in diameter at distances of 60 mm. apart. Each of these holes is lined with a tube of asbestos, and through each passes a

[1] A map of the route, together with detailed descriptions of the machinery and line, and of the tests made by the experts of the commission under Professor H. F. Weber, of Zürich, will be found in the volumes of the Official Report, published at Frankfort in 1893.

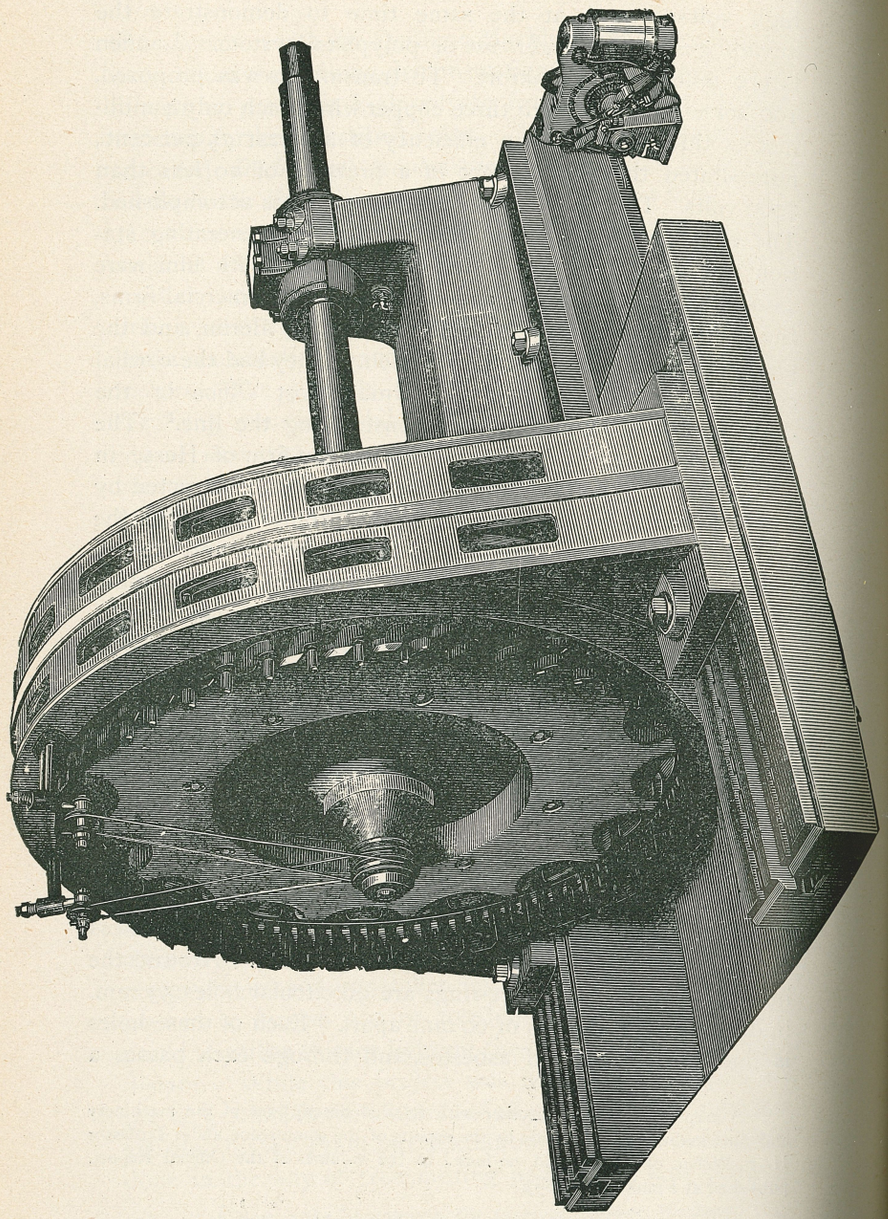

FIG. 344.—BROWN'S THREE-PHASE ALTERNATOR, USED AT LAUFFEN.

solid copper rod 29 mm. in diameter. The core-rings, built up of segmental stampings, are assembled in a strong cast-iron

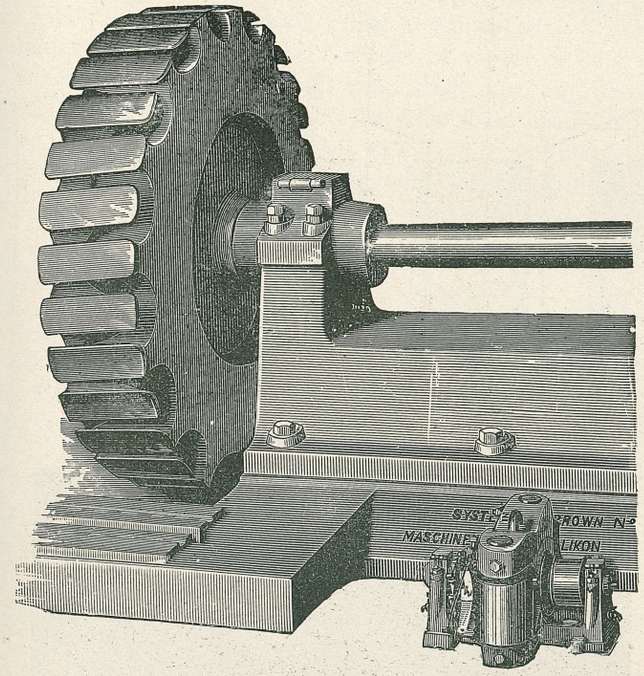

FIG. 345.—FIELD-MAGNET OF THE THREE-PHASE ALTERNATOR AT LAUFFEN.

frame. The winding, if such it can be called, is in three independent zigzags of 32 conductors each, connected according to the following scheme :—

Set A, 1, 4, 7, 10, ...	91, 94.
Set B, 95 92, 89, 86, ...	5, 2.
Set C, 93, 90, 87, ...	3, 96.

The ends of Nos. 94, 2, 96, are connected to a common junction J, while Nos. 1, 95 and 93 are severally brought out to three external terminals. This constitutes a star-winding

(page 52); the connexions of the circuits are shown in Fig. 345, the general arrangement of the windings being illustrated in Fig. 347.

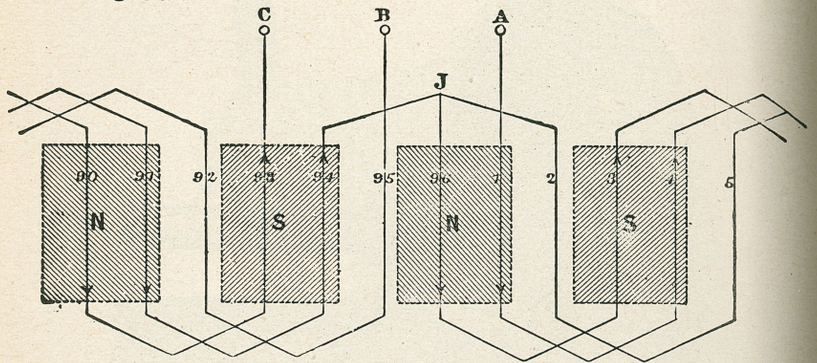

FIG. 346.—DEVELOPED DIAGRAM OF WINDING OF THREE-PHASE ALTERNATOR.

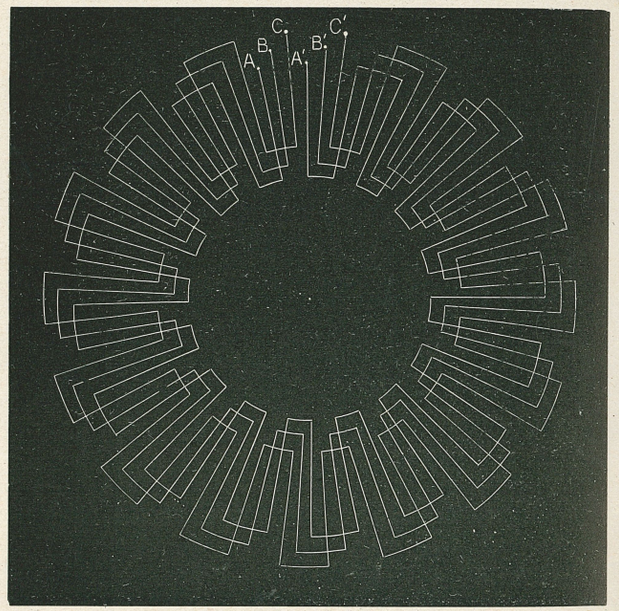

FIG. 347.—ARRANGEMENT OF WINDINGS OF THREE-PHASE ALTERNATOR.

The gap-space between the armature core-ring and the pole-faces of the field-magnet is 6 mm. This field-magnet has 32 poles. It is of great solidity and simplicity, having but a single magnetic circuit. The exciting coil is wound in a channel on the periphery of a sort of pulley of cast iron, to which are bolted two steel rims, each carrying 16 polar expansions or horns. Each of the polar faces has an area of 36 × 16 sq. cm. The channel is 18 cm. wide and 9 cm. deep. In it lie 496 windings of copper wire 5 mm. diameter. A section of this channel is given in Fig. 348; and Fig. 349

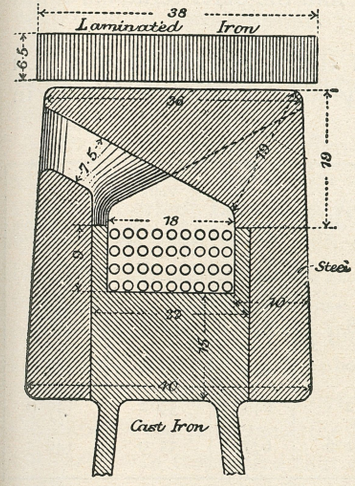

FIG. 348.—SECTION OF FIELD-MAGNET.

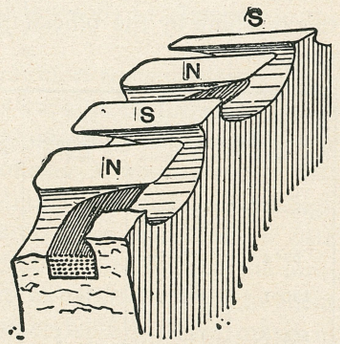

FIG. 349.—SKETCH OF FIELD-MAGNET, WITH IMBRICATED POLE-PIECES.

illustrates the way in which the polar horns project inwardly, the N-poles between the S-poles over the exciting coil. This arrangement reduces the cost of construction and of excitation to a minimum. In fact on open circuit only 100 watts are spent on excitation—one-twentieth of one per cent. of the output; and at full load, when the armature reaction is a maximum, it is still far less than one per cent. This excitation is furnished by a small separate dynamo. The exciting current is conveyed to the rotating part by means of flexible metallic cords running over insulated pulleys, in lieu of the

usual contact-rings and brushes. At full speed and normal voltage, the loss by friction and hysteresis is 3600 watts, or under 1·7 per cent. of the maximum output. The loss by resistance of armature windings at full load is 3500 watts, making total loss about 4 per cent., and commercial efficiency over 95 per cent. The heating is, in the total absence of eddy-currents, quite negligible. The weight is 4½ tons. As there are sixteen pole-pairs, and the speed is 150 per minute, the frequency is 40 periods per second. The electromotive-force generated in each of the three windings, as measured between the common junction J and the outer terminal, could be increased up to 55 volts.

The following are some of the measurements made on this machine by the official jury under Prof. H. F. Weber in 1891.

Horse-power of Turbine.	Electrical Horse-power yielded by Dynamo.	Horse-power lost.	Efficiency.	Current in one circuit.	Volts between common junction and terminals.	Speed Revolutions per minute.
			per cent.			
87·4	75·1	12·3	88	336	54·7	150
120·1	107·5	12·6	90	470	56·1	150
154·7	142·2	12·5	92	641	54·2	149·7
167·2	154·4	12·8	92·6	677	55·9	149·5

The tests were not carried up to full load, but the jury remarked that, assuming the losses to increase in the same proportionality as indicated by the above figures, the efficiency at the full load of 300 horse-power would be 95·4 per cent.

The particular pattern of field-magnet employed in these machines, having only one magnetising coil, and a number of poles imbricated between one another, appears to have been independently devised by Mr. Brown and by Messrs. Gibbs and Fesquet.[1]

[1] See Specification of British Patent, No. 238 of 1889.

It has been used down to the present time by the Oerlikon Company, by Messrs. Alioth, and by several English makers, including Messrs. Johnson and Phillips. It is not, however, altogether satisfactory, for, owing to the inevitable form of the pole-pieces, any armature reactions that may be set up by lagging currents, when working on an inductive load can readily distort the field, and produce considerable magnetic leakage from pole to pole, resulting in a considerable drop in the voltage unless the excitation is largely increased. In fact in all cases where it is undesirable to have such an inductive drop, this form of field-magnet is abandoned. Forms in which each pole, or each alternate pole, is separately wound are less liable to inductive reactions of the kind named. Modern practice is to place the magnetising coils as close up to the polar ends as possible.

To return to the Lauffen-Frankfort transmission. Each of the generators at Lauffen was capable of furnishing three currents, each of 1400 amperes at about 55 volts. In order to transmit this power with economy it was necessary first to transform by means of step-up transformers to the high voltage. Accordingly some three-phase transformers were installed at each end of the line: at Lauffen to raise the pressure to 8500 volts; at Frankfort to reduce it back to about 65 volts. These transformers (some built in Berlin, others in Oerlikon) were immersed, for better insulation, in oil. Their outward form resembled that of the Hochfelden transformers in Fig. 126, page 105. The connections of both low-pressure and high-pressure windings were star-wise, the common junctions being earthed in every case. Fig. 350 gives a diagram that is self-explanatory. The lines were carried on about 3000 poles at a height of about 25 feet, each pole supporting three porcelain insulators with internal rims for holding oil. It crossed territories of four governments, Würtemberg, Baden, Hesse and Prussia, following generally the route of the Neckar Railway, but avoiding the long tunnel through the Odenwald at Krählberg, by going over the mountain. The total weight of copper in the lines was about 60 tons. The construction of the line was carried out under the direction of

Mr. Ebert, Telegraph Inspector of the Imperial Post Office, which co-operated with the Würtemberg Royal Post and Telegraph Service in this undertaking. On August 24, 1891, the line was handed over by the officials to the Oerlikon and Allgemeine Companies, and the following day lamps in the Frankfort Exhibition were lit up by the power from Lauffen. In the exhibition there was a 100 horse-power three-phase motor (Fig. 351), designed by von Dolivo-Dobrowolsky, and constructed by the Allgemeine Company, and other smaller motors, to which allusion has already been made above. This motor worked a centrifugal pump, taking about 60 horse-power, raising water for an artificial waterfall about

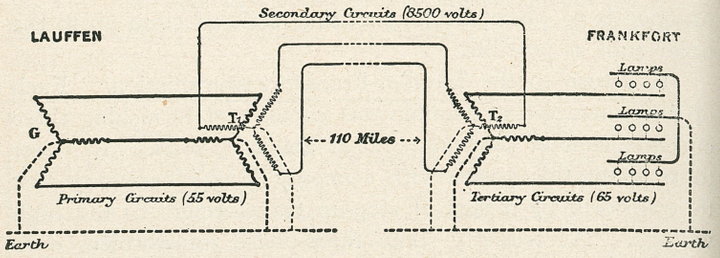

FIG. 350.—CIRCUITS OF THE LAUFFEN-FRANKFORT TRANSMISSION.

33 feet high in the grounds of the exhibition. In addition to these motors, there were about 1000 glow-lamps operated by the current so transmitted.

Great scepticism prevailed at first as to the probable result of the transmission under the novel conditions of using such very high voltages over so long a line, and with polyphase currents. It was anticipated by some that the efficiency would be greatly reduced by possible disturbances due to the capacity of the lines acting as condensers, or to leakage over the 10,000 insulators on which the line was supported. In private, some who were very closely connected with the enterprise expressed their fears lest the efficiency should fall below 50 per cent., and at one time there was some apprehension lest the jury would not be allowed to make full tests. However, as experience was gained these fears were found to be

empty. The elaborate tests carried out by the commission in the autumn months, mostly at about 8000 volts pressure,

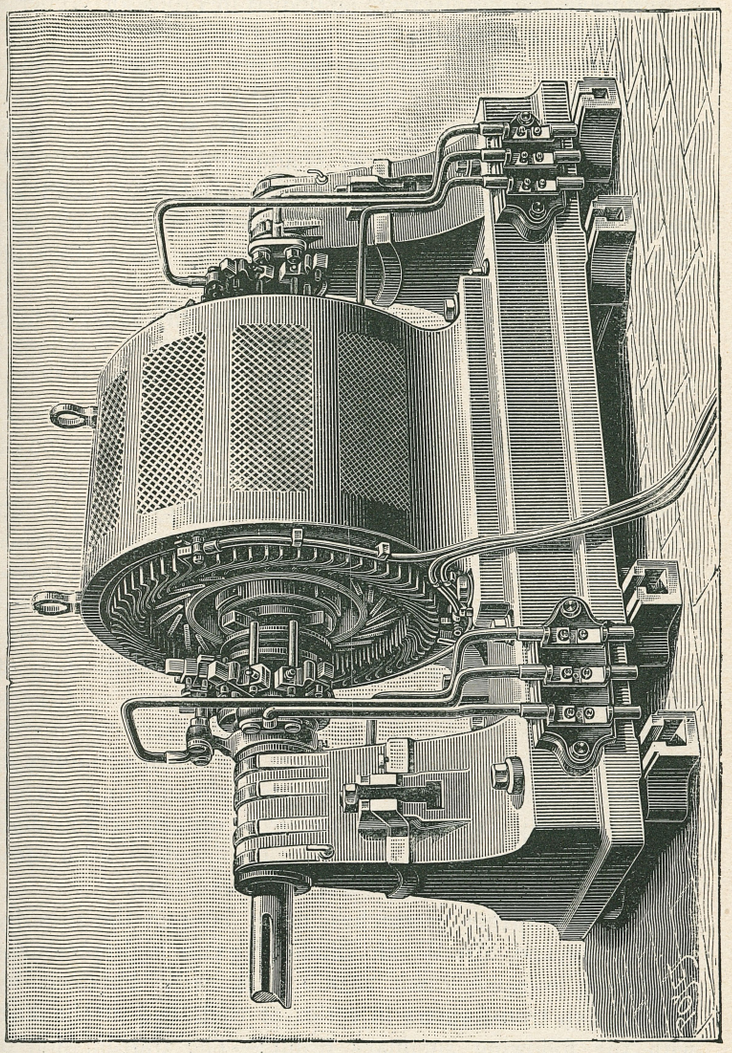

FIG. 351.—DOBROWOLSKY'S 100 HORSE-POWER THREE-PHASE MOTOR.

showed that the energy given out electrically at Frankfort was as much (on the average) as 74 per cent. of the energy given

by the turbines at Lauffen to the generator. The various sources of loss were ascertained and carefully measured, and the results of the various tests embodied in Professor Weber's report. It concludes with the following summary:—

1. In the Lauffen-Frankfort plant for the electric transmission of energy over a distance of 170 kilometres, by means of a system of alternating currents, with a pressure of 8500 to 7500 volts, and bare copper conductors insulated by oil and porcelain, the lowest output in the tertiary circuit at Frankfort was 68·5 per cent., and the highest output was 75·2 per cent., of the energy given out by the turbine at Lauffen.

2. In this transmission to a distance the only cause of loss measurable by the instruments was that due to the resistance of the circuit (Joule's effect).

3. Theoretical considerations showed that the influence o capacity upon long aerial bare conductors for transmission of energy to a distance by alternate currents, under the conditions employed, and with use of a frequency of 30 to 40 periods per second, is of so entirely subordinate a magnitude that it need not be considered in designing electric transmissions.

4. As the expression of our experience during the foregoing measurements for the determination of the efficiency of the Lauffen-Frankfort transmission of energy we add, as a fourth result:—The electrical running with alternate currents of 7500 to 8500 volts in conductors of more than 100 miles in length, insulated by means of oil, porcelain and air, proceeds just as regularly, safely, and as free from disturbances as does running with alternate currents of a few hundred volts pressure over conducting wires of a few metres length.

In some further researches made later in the year by Dr. Kittler and Mr. W. H. Lindley,[1] extra high pressures, exceeding in some cases 28,000 volts, were obtained by putting two transformers in series at each end of the line, with the following summary result:—The transmission of power from Lauffen to Frankfort, with a high pressure of

[1] Official Report of the Frankfort Exhibition, ii. p. 451.

25,000 volts (from line to line, or at 14,000 to 15,000 volts between lines and earth), and with a frequency of 24 periods per second, gave an efficiency of about 75 per cent. with a load of about 180 horse-power.

The Lauffen-Frankfort transmission was much more than a mere experiment. It was a daring and successful demonstration not only of the utility of high voltages in the transmission of power, but of the success of polyphase currents. As such it marked an epoch in the commercial development of electricity. It evoked an extraordinary interest throughout the continent of Europe, and in Germany in particular. One evidence of this is to be found in the circumstance that early in the history of the project the German Emperor himself made a contribution of 10,000 marks toward the cost of the scheme.

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